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Aerodynamic Interference Caused by the Inboard Leading-Edge Flap on the Outboard Area of the Cranked Arrow Wing

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Abstract

Wind tunnel tests were conducted on a cranked arrow wing model to reveal the relationship between the inboard leading edge flaps and vortex behavior formed on the outboard wing area. Aerodynamic force measurements and flow visualizations on the upper surface of the wing were made. The pitching moment characteristics indicate that there are two non-linear changes and the flow patterns which caused those changes are observed. The flow patterns indicate that the non-linear changes are caused both by the flow separation on the outside of the inboard vortex and by the one on the outside of the merging position of the inboard and outboard vortices. It was found that the inboard leading edge flap decreases the angle of attack when recovery from the first change occurs. The inboard leading edge flap also causes an increase in the magnitude of the second change.

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Keywords: Cranked-Arrow Wing; Separation Vortex; Leading-Edge Flaps; Flow Visualization

1. Introduction

It is known that the cranked-arrow wing indicates some non-linear changes in aerodynamic characteristics at low speeds and at high angles of attack because of the effect of the two leading-edge separation vortices originating from the wing apex and leading edge kinks [1]. Though it produces additional lift induced by the suction force of the vortex, it also indicates the nonlinear pitch up trend that causes the loss of the longitudinal stability of the aircraft at high[2]. Therefore, it is important to predict where non-linear changes occur at [3]. One of the causes of the changes is the flow separation on the outboard wing [2]. Due to interference between the inboard and outboard vortices on

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the outer wing, the outboard vortex rises from the wing surface and aerodynamic forces on the outer wing are reduced. Because the outboard wings are generally located at rearward locations, the changes to the pitch-up direction and the wings lose their stability. Some studies visualizing the flow field on a double delta wing indicate that the merging of the two vortices is observed when non-linear change occurs [4,5].

In a previous study, it was found that the inboard leading-edge flap improves the non-linear characteristics of the cranked arrow wing [6]. This study indicated the relationship between the outboard flow and the deflection angle of the inboard leading-edge flap. According to experimental results in reference [7], the deflection of the inboard leading edge flap has two trends of non-linear change as the flap deflection angle increases. First is the increase in where the change occurs and the second is the increase in the amount of change. However, the previously proposed prediction model for estimating aerodynamic characteristics of the cranked arrow wing in reference [3] did not consider the effect of the inboard leading-edge flap on the nonlinear change induced by the flow separation on the outboard wing. In this paper, to investigate the effects of the inboard leading edge flap on vortex behavior and outboard flow, wind tunnel tests were conducted. The flow patterns on the outboard wing were visualized by using the oil flow technique and aerodynamic forces were measured.

Nomenclature

lift coefficient
pitching moment coefficient at 25% *MAC*
angle of attack
deflection angle of the inboard leading-edge flap
mean aerodynamic chord
neutral point location normalized by *MAC*

2. Wind Tunnel Experiment Details

Figure. 1 shows the details of the wind tunnel model used in this study. It had a wing-body configuration and the same planform which was designed preliminarily for a supersonic experimental airplane at the Institute of Aeronautical Technology of the Japan Aerospace Exploration Agency (JAXA) [8]. The model had a cranked arrow wing configuration with the fuselage and the wing cranked at the 55% semi-span station. The sectional airfoil was made of flat plates which have a constant thickness of 10mm. All edges of the wing were cut off in two phases as shown in Fig. 1 section A-A. The aspect ratio and *MAC* of the wing were 2.42 and, respectively. In this study, only the inboard leading-edge flaps were deflected. The inboard leading-edge flaps had a constant chord length of 10% *MAC*, and the outboard leading-edge flaps had 20% local chord length of the outboard wing at its span station. The flap deflection angle was defined as normal to the hinge line. The configuration with undeflected flaps is called baseline in this paper.

The tests were conducted in the low speed wind tunnel located at JAXA. The tests were conducted at a free stream velocity of 30 m/s and a Reynolds number based on *MAC* of 8.7×10^5. Six component aerodynamic forces were measured in the range of and flow patterns on the upper surface of the wing were visualized at by the oil-flow technique. The tested flap deflection angle is . The magnitude of non-linear characteristics can be represented by the change of neutral point location. is the point where the pitching moment is not changed regardless of the change of and is represented by following equation (1).

$$N_0 = 0.25 - \frac{dC_m}{dC_L} \quad (1)$$

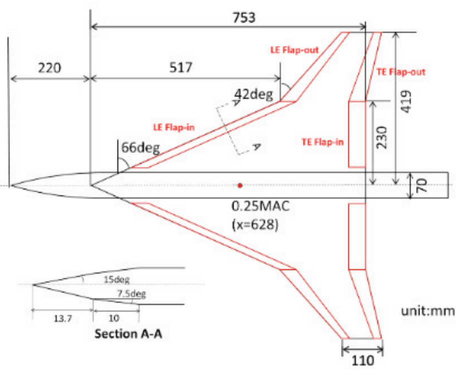


Fig. 1. The configuration used in the tests

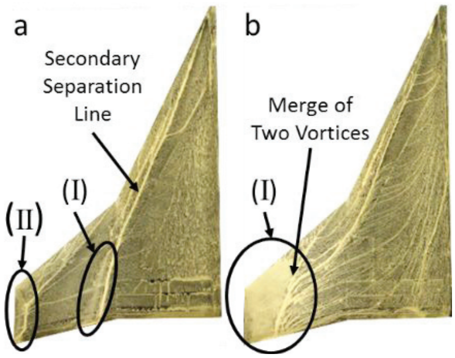


Fig. 3. The oil-flow patterns on upper surface of baseline configuration. (a) ; (b)

If the slope of the Cm-CL curve nonlinearly increases, would move forward and the amount would be reduced. The amount of change of represents the impact of non-linear change and loss of longitudinal stability.

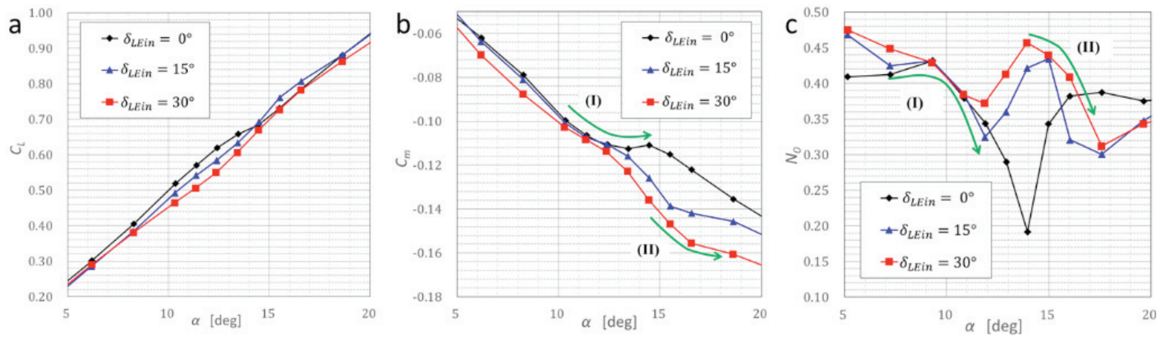
3. Results and Discussion

Figure. 2 shows the results of and characteristics of the baseline and the configurations with the deflection of the inboard leading-edge flap within the range of . The linear pitching moment (Fig. 2b) and stable (Fig. 2c) are observed in the range of for all configurations. In the range of , the of the configuration with inboard leading edge flap deflection represents more pitch down characteristics than that of the baseline. It indicates that the outboard vortex develops earlier as the flap deflection angle increases. At , the decreases as the deflection angle of the flap increases (Fig. 2a), though the changes in are not seen. This fact expresses the loss of lift on the whole wing and it is thought that this loss is caused by the loss of suction force induced by the inboard vortex. Therefore, the inboard leading edge flap has an effect on the restraint of inboard vortex development as well as on the promotion of outboard vortex development.

In the range of of no less than, Figs. 2b and 2c indicate that two non-linear pitch-up changes, indicated by green arrows, occurred and the behavior of the changes are different by the deflection angle of the flap. Each change is discussed below based on the correspondence of measured aerodynamic forces and observed flow patterns.

The first change is observed at ((I) in Fig. 2b, 2c)). The on the baseline configuration () changes drastically to pitch up direction and moves greatly to forward. Figure 2a also shows this change causes a loss in lift. Since such abrupt change was not measured in the previous study that used the model with a warped wing [7], it is considered that this change is peculiar to this flat plate model. Though this non-linear change also occurred in the configuration with deflection of the flap, Fig. 2b indicates that the magnitude of the changes is reduced by the deflection angle of the flap. Moreover, Fig. 2c indicates the begins to return to its original position of a low at around and the amount of change of is lower than that of the baseline configuration. This means the inboard leading edge flap has the effect of decreasing at the beginning of recovery from the first change as well as to reduce the magnitude of that change.

Fig. 3a shows the oil-flow pattern on the upper surface of the baseline configuration at . Two vortices originated from the wing apex and the leading edge kink formed on the wing. The separated region is observed on the outside of the inboard vortex secondary separation line (Fig. 3a (I)) and at the wing tips (Fig. 3a (II)). Figs. 4a ~ c show sketches of oil-flow patterns at for different flap deflections. The inboard vortex secondary separation line moves outward after the leading edge kink location and two secondary separation lines merge on the outboard wing of the configuration with the deflection of leading edge flap (). This fact represents that where the vortex interaction occurred decreases as the inboard leading edge flap deflects. The cause for the decreasing of where the vortex



Figs. 2. Lift (a)pitching-moment; (b) and neutral point ;(c) characteristics for the configuration with the deflection of inboard leading edge flap.

interaction occurred may be that the distance between the two vortices shrinks due to the movement of the inboard vortex core outward and of the outboard vortex core inward by the effect of the leading edge flap. Figures 4a ~ c indicate that the inboard vortex's spanwise width gets smaller as the deflection angle of the flap increases and the secondary separation lines do not move. It represents the effect of the leading edge flap to restrain the vortex development and thus the inboard vortex core moves outward. Figures 4a ~ c also indicate that the outboard vortex is formed inwardly and it is caused by the restraint of the spanwise flow on the outer wing induced by the suppression of inboard vortex development when the leading edge flap is deflected.

In reference [6], it is concluded that there are two causes of the first change, and the flow separation at the wing tip was one of them. However, in this test, the separated region at the wing tip is observed on all configurations at (figs. 4) though fig. 2c indicated that returns to its original position of a low at for the configuration with flap deflection. On the other hand, fig. 4 also indicates that the separated region on the outside of the inboard vortex disappears due to the occurrence of the merging of the two vortices in this configuration at . Therefore, it is thought that the one of causes for the first non-linear change is the separated region located not at the wing tip but on the outside of the inboard vortex.

The inboard vortex breakdown was also concluded as being another factor of this first non-linear change in reference [6]. The vortex breakdown is known as the cause of the drastic loss of vortex suction force at the rear part of the wing and induces a pitch up change in the pitching moment. According to reference [9], the where the vortex breakdown occurs at is increased with the increasing of the sweep back angle and the breakdown occurs at about for the delta wing. However, since the occurrence of inboard vortex breakdown is promoted by the occurrence of outboard vortex breakdown [4], it is considered that the inboard vortex breakdown occurred at a low on the cranked arrow wing compared with the delta wing as in reference [6]. Moreover, since the vortex interaction is promoted by flap deflection, the inboard vortex breakdown may also be promoted. On the other hand, the occurrence of inboard vortex breakdown is restrained by the effect of the leading edge flap because effectively decreases. This effect may cause the magnitude of change reduction seen in fig. 2b. Therefore, the inboard vortex breakdown is affected by two contrary effects of the inboard leading edge flap deflection and may influence non-linear change. However, the occurrence of vortex breakdown cannot be detected by the flow pattern on the upper surface of the wing and it is difficult to conclude what the full effects of vortex breakdown on this change are in this paper.

The second non-linear change is seen at ((II) in Fig. 2b, 2c)). Fig. 2b indicates that the slope of of the configuration with the flap deflection () changes to the pitch up direction and loses longitudinal stability. The behavior of this change is similar to the one that was pointed out in previous study [2]. Fig. 2c indicates that moves forward again after recovery from the first change in those configurations. However, this change is not observed in the baseline configuration () because the first change was so strong that the two changes occurred continuously. Therefore, it is thought that the recovery of the first change and the beginning of the second change occur at the same . Fig. 2b also indicates that the where the second change occurs at is getting higher as the deflection angle of the flap increases. The at where the slope of is changed by the second change is for , for and for . Accordingly, it is thought that the inboard leading edge flap has the effect of increasing where the second change occurs. Moreover, Fig. 2c indicates that the magnitude of change of gets larger as the flap is deflected. Though the original location of is the same at regardless of the deflection of the flap. The locations of after the second change occurrence () in the configuration with the flap deflection are more forward than that of the baseline configuration. It

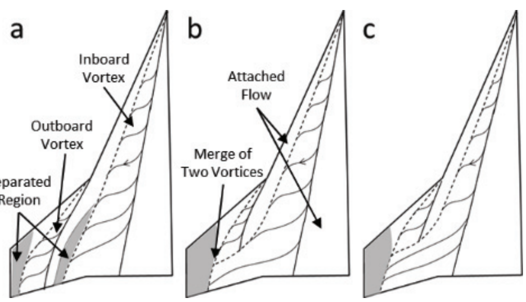


Fig. 4. The sketch of flow patterns at .
(a) ; (b) and (c) .

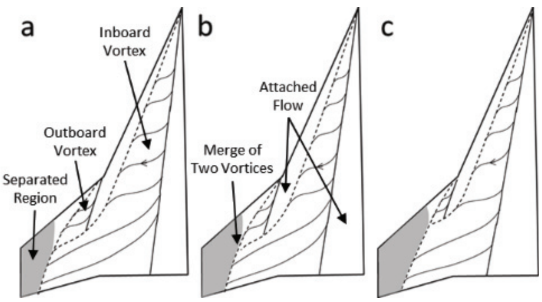


Fig. 5. The sketch of flow patterns at .
(a) ; (b) and (c) .

can be said that the inboard leading edge flap has the effect of increasing the intensity of the second change.

Fig. 3b shows the oil-flow pattern on upper surface of baseline configuration at . The separated region on the outside of the merging point is observed (Fig. 3b (I)). Figures 5a ~ c show sketches of oil-flow patterns at . The two vortices are merging on the outer wing and the separated region on the outside of the merging point is observed in all configurations. Therefore, it is thought that the separated region of the outside of the inboard vortex is the cause of the second change. The location of merging moves forward and the area of the separated region increases as the deflection angle of the inboard leading edge flap increases. This is because the outboard vortex formed inward due to the reduction of spanwise flow on the outboard wing. It is the effect of the leading edge flap on the restraint of inboard vortex development. Since Fig. 2c indicates that the magnitude of change of gets lower as the flap deflection angle increases, it is thought that the magnitude of change has a positive correlation with the area of the separated region.

4. Conclusions

Wind tunnel tests were conducted on the cranked arrow wing model. Aerodynamic forces were measured and flow fields on three configurations with different deflection angles of inboard leading edge flaps were visualized. The objective of this paper is to reveal the inboard leading edge's effect on the nonlinear change induced by the flow on the outboard wings. The results lead to the conclusions described below.

1) The inboard leading edge flap induces the two significant effects on the restraint of inboard vortex development and on the promotion of outboard vortex development.
2) Two nonlinear changes of the aerodynamic characteristics were observed at and .
3) The first change is caused by the flow separation on the outside of the inboard vortex. The inboard leading edge flap has the effect of decreasing at the beginning of recovery from the change and of reducing the magnitude of change. Those effects are induced by the outward movement of the inboard vortex and the inward movement of the outboard vortex due to the restraint of inboard vortex development. It is considered that the outboard vortex breakdown is also the factor of this change and this change is peculiar to the flat plate model in this study.
4) The second change is caused by the flow separation on the outside of the merging point of the two vortices. The inboard leading edge flap has the effect of increasing the amount of the second change because the area of separation is increased by the flap deflection.

References

[1] Grafton, S. B., "Low-Speed Wind-Tunnel Study of the High-Angel-of-Attack Stability and Control Characterisitcs of a Cranked-Arrow-Wing Fighter Configuration", NASA TM -85776, 1984.

[2] Benoliel, A. M. and Mason, W. H., "Pitch-up Characteristics for HSCT Class Planforms: Survey and Estimation", AIAA-1994-1819-CP, 1994.

[3] Toyoda, K., Rinoie, K., Kwak, D., " Estimation Methods for Low Speed Aerodynamic Performance of Cranked Arrow Wing with Leading- and Trailing- edge Flaps", Proc. of JSASS annual meeting, C06, 2014.(in Japanese)

[4] Thompson, D. H., ''A Visualization Study of the Vortex Flow around Double-Delta Wings'', ARL-AEROR-165, 1985.

[5] Brennenstuhl, U., Hummel, D., "Vortex Formation Over Double-Delta Wings", ICAS-82-6.6.3, Aug. 1982.

[6] Zhao, W., Kwak, D., Rinoie, K., "Studies on Improvement of Nonlinear Pitching Moment Characteristics of Cranked-Arrow Wing", ICAS-2012-3.2.1, Sept. 2012.

[7] Kwak, D., Miyata, K., Noguchi, M., Sunada, Y., Rinoie, K., "Experimental Investigation of High Lift Device for SST", NAL-TR-1450, 2002. (in Japanese)

[8] Yoshida, K. and Makino, Y., "Aerodynamic design of unmanned and scaled experimental airplane in Japan", ECCOMAS 2004, 2004.

[9] Gursul, I., Wang, Z., and Vardaki, E., "Review of Flow ControlMechanisms of Leading-Edge Vortices", Progress in AerospaceSciences,Vol.43, pp.246-270, 2007.